1416

BENTHIC INVERTEBRATE COMMUNITY STRUCTURE AND SEDIMENT BIOASSAYS OF CHEMICALLY TREATED AND UNTREATED SEDIMENT FROM HAMILTON HARBOUR

JANUARY 1991

Ontario
Environment
Environnement

ISBN 0-7729-7809-3

BENTHIC INVERTEBRATE COMMUNITY STRUCTURE AND SEDIMENT BIOASSAYS OF CHEMICALLY TREATED AND UNTREATED SEDIMENT FROM HAMILTON HARBOUR

Report prepared by:
Gail Krantzberg
Great Lakes Section
Water Resources Branch
Ontario Ministry of the Environment

January 1991

RECYCLABLE

Cette publication technique
n'est disponible qu'en anglais

PIBS 1416
log 90-2320-065

Foreword

In its 1985 report to the International Joint Commission (IJC), the Great Lakes Water Quality Board recommended that the appropriate jurisdictions prepare and submit detailed Remedial Action Plans (RAPs) for the restoration of beneficial uses of 42 identified "Areas of Concern" on the Great Lakes system. Hamilton Harbour is one of the "Areas of Concern".

The RAP team in its 1989 Stage I report identified zones of highly contaminated sediment and presented results of a number of toxicity tests on Hamilton Harbour sediment. The cause of the toxicity was not readily attributed to any specific class of compounds. Hamilton Harbour sediment is a complex mixture of metals and trace organics. As well, anaerobic conditions are generated in the hypolimnion during the summer months. In order to develop options for sediment remediation, further knowledge of the causal links between sediment conditions and toxicity was required.

This report presents the results of chronic sublethal toxicity tests conducted on untreated and chemically treated Hamilton Harbour sediment in conjunction with information on the benthic community composition. This information has been presented to the Hamilton Harbour RAP team. Their comments have been incorporated into the report.

This report is intended to serve as a background reference document. It provides useful information that could assist the RAP team and the public in evaluating options and in ultimately defining a remedial action plan for the harbour. The results will be incorporated into the Stage II report for the Hamilton Harbour RAP.

Acknowledgements

Analysis of treated sediment was made possible by the cooperation of T. Murphy of the National Water Research Institute. S. Petro and B.A.R. Environmental Consultants conducted the sediment bioassays and BEAK Consultants Ltd. collected and identified the benthic invertebrates. I thank D. Boyd for assistance in the development of the study. Members of the Water Resources Branch provided valuable suggestions in their review of the manuscript.

EXECUTIVE SUMMARY

Sediment from regions within Hamilton Harbour is highly contaminated with metals, nevertheless, not all metal contaminated sites were highly toxic to test organisms. Most sediment did elicit sublethal and/or lethal responses in bioassay organisms. Results of analyses of tissue residues in test organisms and the amelioration of toxicity by chemical treatment implicate trace metals as contributing to sediment toxicity. Sediment oxygen demand, however, apparently contributed to the restricted benthic community *in situ* and some of the toxicity observed *in vitro*. For some stations, there was evidence that PAHs were responsible for the deleterious effects detected. The suitability for colonization by benthic invertebrates of sediment in some areas of Hamilton Harbour may be limited by both contaminants and high sediment oxygen demand. Remedial options aimed at improving the oxygen regime of the harbour should result in improvements in the benthic invertebrate community directly, by providing a suitable oxygen regime for organisms less tolerant of temporal anoxia, and indirectly by decreasing metal bioavailability, possibly through the coprecipitation of trace metals with iron and manganese hydroxides.

Introduction

Trace metals and organic compounds in a substantial area of the sediment of Hamilton Harbour exceed the Ministry of Ontario draft sediment guidelines which identify the "severe effects level" (Persaud et al 1990). This is the level at which significant biological impacts are anticipated. These concentrations for total PAH, Cr, Cu, Pb and Zn are 550 (normalized for sediment TOC of 5%), 111, 114, 250 and 800, respectively. Concentrations in the harbour reach a maximum of approximately 700 (TOC 5%), 500, 160, 700 and 4500 for PAH, Cr, Cu, Pb, and Zn, respectively (Rodgers et al 1989). From this one would anticipate significant environmental damage and a necessity to develop remedial options aimed at removing the toxicological threat.

Chemical measurements, however, have been shown to be limited in their use for predicting environmental effects due in large part to the biotic and abiotic factors that mediate metal bioavailability and toxicity. Numerous studies have demonstrated that the geochemistry of a particular system is important in metal speciation (Luoma 1983, Tessier et al 1984, Morse et al 1987, Davis-Colley et al 1985, Campbell et al 1987, Krantzberg and Stokes 1988). This has led to recommendations that biological tests be performed when chemical measurements indicate the potential for adverse environmental impact (Chapman 1989, Landner 1988, International Joint Commission 1988, van Veen and Stortelder 1988, Karr 1987, Persaud et al 1990).

Due to the large volume of contaminated sediment in the harbour, it is unpractical to recommend dredging and disposal of all sediment that exceed the draft provincial guidelines that identify the "severe effects level". It would be extremely useful to be able to determine the extent to which sediment that has contaminants that exceed this level are biologically available and are having repercussions for the health of the biota.

The principle study objectives were to establish whether contaminants in the harbour are biologically available, to compare the biological response of test organisms to harbour sediment with sediment chemistry, to relate toxicity observed in bioassays to benthic community structure *in situ*, and to evaluate tissue residues of contaminants in test organisms in light of sediment contamination.

A preliminary evaluation of the source of toxicity was investigated by selectively treating sediment with compounds designed to immobilize polar compounds, and comparing the results of bioassays using treated and untreated sediment.

Materials and methods

Sediment collection

In phase one of the study, sediment was collected by Ekman grab from five stations in the harbour and one station situated in Lake Ontario approximately 1 km northeast of the mouth of the harbour (Burlington Ship Canal) in December 1988 (Figure 1). Each station was sampled on two separate occasions during phase one in order to provide information on the variability introduced as a consequence of station relocation. Station numbers are denoted with 1 or 2, thereby indicating on which visit the samples were collected. Phase two, the toxicity evaluation experiment, required the collection of bulk sediment for chemical treatment. Stations were visited once during this phase of the study. For both phases, the surface 2 cm were removed from each grab using acid-washed polyethylene or glass beakers or plastic spoons. Approximately 20 L of surficial sediment was placed in plastic lined collection buckets which were then sealed, kept cold in the field, and stored for no more than two weeks (phase one), or treated and then stored at 4 C for six weeks (phase two).

Sediment pH, Eh and temperature were measured at time of collection. In order to minimize disturbance of the sediment, all measurements were performed while the sediment remained in an Ekman grab. The pH readings were taken with a Cole-Parment digital pH meter, while Eh was measured with an Orion millivolt

TABLE 1: PARAMETERS FOR HAMILTON HARBOUR BULK SEDIMENT SAMPLES

Station-Visit	Temperature (^oC)	pH	Eh (MV)
270-1	6	7.11	+65
270-2	6	7.53	+85
258-1	7	7.36	+35
258-2	7	7.41	+45
255-1	7	7.28	+50
255-2	7	7.38	+45
4-1	6	7.40	+45
4-2	7	7.28	+60
268-1	9	6.61	+105
268-2	10	6.90	+125
Outer Harbour-1	4	7.58	+155
Outer Harbour-2	4	7.32	+105

meter equipped with a calomel electrode coupled with a salt bridge and a platinum electrode.

Collection of macroinvertebrates for analysis of community composition

During phase one, at each harbour station and for each visit, five Ekman grabs (22 cm x 22 cm) were collected, sieved through a 500 um screen and pooled in a 1 L container. Due to the nature of the sediment at the station in the outer harbour it was necessary to use a Ponar grab. All samples were preserved in 10% formalin and stained.

Samples were sorted under a stereomicroscope (10 x) into major taxonomic groups. Oligochaetes were identified to species while all other taxa were identified to genus with the exception of Nematoda, Turbellaria and Hydracarina. Chironomidae were decapitated and mounted in a permanent clearing mountant prior to identification. Oligochaetes were subsampled and 75 to 100 individuals from each sample were mounted in a permanent clearing mountant and identified to species. Species densities were expressed per meter squared and each species present in a sample was ranked according to its numerical dominance within that sample.

Toxicity evaluation experiment: chemical treatment of sediment

During phase two, at stations 270, 258, 256 and 13, sediment was treated with either iron, alum, oxygen, slag, or lime (Murphy, National Water Research Institute, pers. comm.). Untreated aliquots were also retained to permit a comparison of toxicity of the original sediment with that of treated material. Sediment treatements consisted of:

1. Oxygen bubbling to saturation
2. Slag addition of 5 $g.l^{-1}$ wet sediment
3. $FeCl_3$ addition of 250 $mg.l^{-1}$ wet sediment
4. Alum (Al_2SO_4) addition of 250 $mg.l^{-1}$ wet sediment
5. Lime ($CaOH_2$) addition of 250 $mg.l^{-1}$ wet sediment.

Sediment was treated for 6 weeks before beginning the bioassays. Jars were gently shaken once a week.

Sediment bioassays

Sediment bioassays employed a static beaker design. Test organisms were mayfly nymphs (*Hexagenia limbata*) weighing approximately 30 $mg.individual^{-1}$ (wet weight), 3 to 4 month old juvenile fathead minnows (*Pimephales promelas*) weighing approximately 400 $mg.individual^{-1}$ wet weight and in the case of the treated sediment experiments, egg-sac stage rainbow trout (*Salmo gairdneri*). Growth, mortality, and bioaccumulation of contaminants were the endpoints measured. The sediment bioassay protocol followed the protocol detailed by

Krantzberg (1990a). Two-litre wide mouth glass jars of surface area 100 cm^2 were filled to a depth of 3 cm with sediment and 1,200 ml of deionized water to obtain a water:sediment ratio of 4:1 (v/v). The sediment and water mixtures were allowed to settle for 24 hours. Aeration was provided one hour prior to addition of the test organisms and continued throughout the duration of the experiment. Water loss due to evaporation was replaced as necessary to retain the appropriate volumetric ratio of water to sediment. Dissolved oxygen, pH, conductivity and temperature were monitored routinely during the experiments.

The exposure duration was 21 days at which time the beakers were harvested for surviving individuals. Ten individual mayflies or fathead minnows were allocated to triplicate bioassay chambers assembled for each station, each visit, and treated sediment. Triplicate containers of fifty egg-sac stage rainbow trout were prepared, and rainbow trout were suspended directly above the sediment in nylon mesh bags.

Initial biomass was estimated based on five randomly collected samples of organisms. Final biomass was determined for individual beakers. Where biomass was insufficient for chemical analysis, the biota for the triplicate beakers were pooled. Different species were not pooled together. Organisms for trace organic and metal analysis were wrapped in hexane-rinsed aluminum foil and plastic, respectively, and frozen until analysis. Honey Harbour sediment (Georgian Bay, Lake Huron), the site from which mayflies were

collected for use in the bioassays, was used to monitor control growth and mortality.

Results and Discussion

Benthic community structure

All stations within Hamilton Harbour were dominated by low oxygen tolerant oligochaetes, primarily Limnodrilus hoffmeisteri, L. cervix, Tubifex tubifex and Quistradrilus multisetosus. Eh measurements of the sediment were all marginally positive, indicating that surface sediment was slightly oxic (Table 1), however Eh values could be misleading as a consequence of sediment handling, in spite of efforts to minimize disturbance of the sediment. The anoxic odour noted during collection suggests that the sediment would have had negative Eh values *in situ*.

Station 268 located at the mouth of Windermere Basin had the highest density of oligochaete species with 21,000 individuals.m^{-1}, indicative of high organic enrichment (Table 2). This station is in close proximity to the Woodward Avenue sewage treatment plant outfall. Macroinvertebrate communities at Station 255 and station 4 were dominated by immature tubificids without hair setae and are likely to be L. hoffmeisteri and L. cervix. Station 255 was the only station within the harbour where Gammarus was found. The presence of this organism is indicative of oxic conditions at the sediment-water interface.

The outer harbour station had the highest species diversity, with Pisidium being the dominant invertebrate. Species such as Potamothrix moldaviensis, P.

vejdovskyi, Spirosperma ferox and Stylodrilus heringianus found in the outer harbour station are all oligochaete fauna that indicate moderately enriched sediment quality.

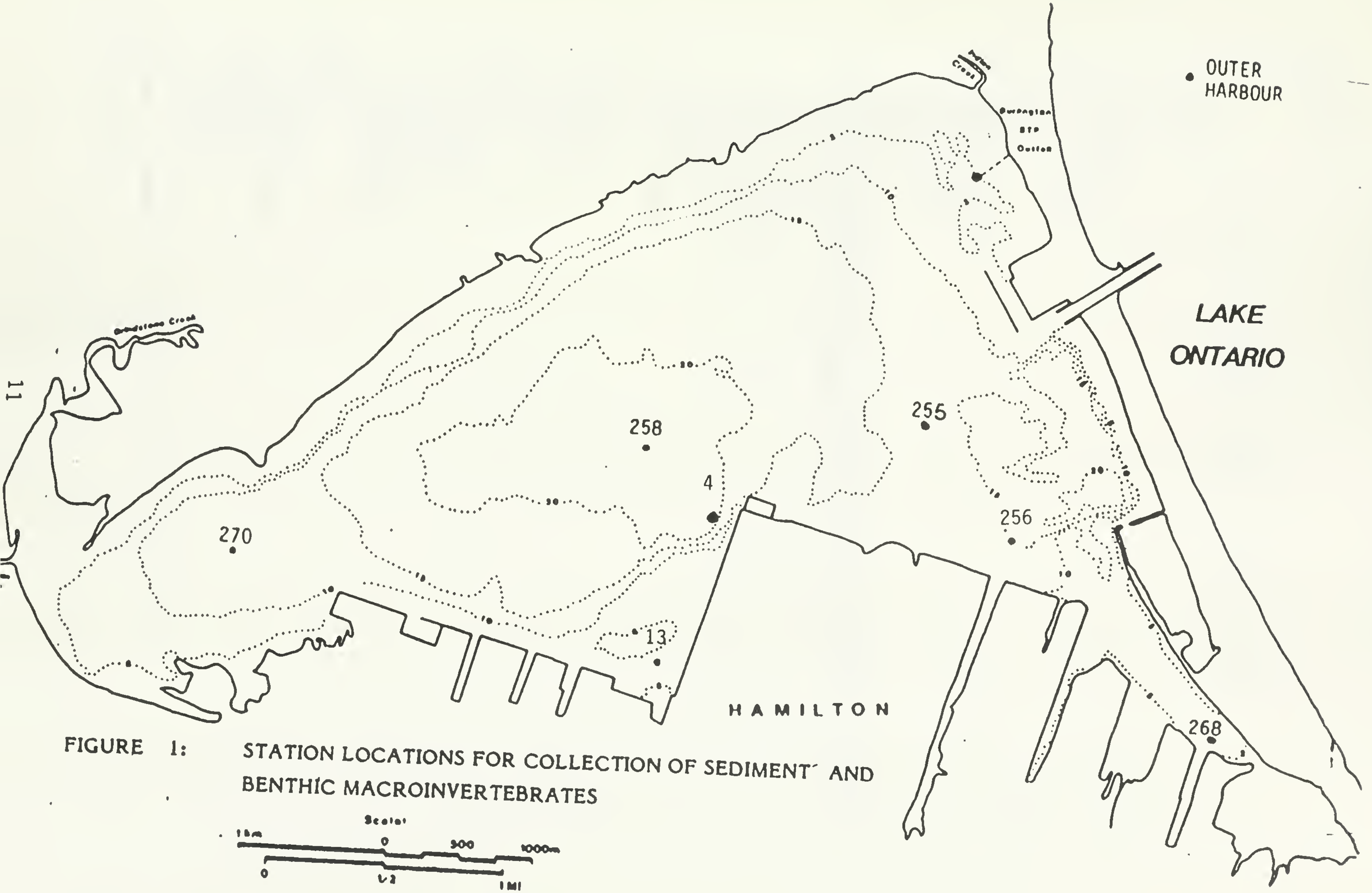


FIGURE 1: STATION LOCATIONS FOR COLLECTION OF SEDIMENT AND BENTHIC MACROINVERTEBRATES

TABLE 2. BENTHIC MACROINVERTEBRATE COMMUNITY COMPOSITION
STATIONS SAMPLED NOVEMBER 1988

BENTHIC DATA FOR STATION 258, LOCATED IN THE CENTRAL REGION OF HAMILTON HARBOUR

Station 258

Visit	1		2	
Species	No./m^2	Rank	No./m^2	Rank
P. Coelenterata				
F. Hydridae				
Hydra sp.				
P. Platyhelminthes				
Cl. Turbellaria				
O. Tricladida sp. indet.				
P. Nematoda sp. indet.				
P. Annelida				
Cl. Oligochaeta				
F. Naididae				
Chaetogaster diaphanus				
Ophidonais serpentina				
Stylaria lacustris				
Arcteonais lomondi				
Dero nivea				
F. Tubificidae				
Tubifex tubifex	670	3	92	5
Potamothrix moldaviensis				
Potamothrix vejdovskyi				
Limnodrilus hoffmeisteri	2,197	2	4,015	1
Limnodrilus cervix				
Ilyodrilus templetoni				
Spirosperma ferox				
Quistadrilus multisetosus	287	5	375	4
Immature with hair setae	478	4	654	3
Immature without hair setae	3,819	1	1,776	2
F. Lumbriculidae				
Stylodrilus heringianus				
Cl. Hirudinea				
F. Glossiphoniidae				
Helobdella stagnalis				
P. Arthropoda				
Cl. Crustacea				
O. Amphipoda				
F. Gammaridae				
Gammarus sp.				
Cl. Arachnida				
O. Acarina sp. indet.				
Cl. Insecta				
O. Diptera				
F. Chironomidae				
pupae sp. indet.				
Procladius sp.				
Chironomus sp.				
Paratanytarsus sp.	4	6		
Micropsectra sp.				
Dicrotendipes sp.				
Heterotrissocladius sp.				
P. Mollusca				
Cl. Gastropoda				
F. Valvatidae				
Valvata piscinalis				
Valvata sincera sincera				
Cl. Pelecypoda				
F. Sphaeriidae				
Sphaerium sp.				
Pisidium sp.				
Total Number of Organisms	7,455		6,912	
Total Number of Taxa	6		5	

BENTHIC DATA FOR STATION 4, LOCATED 500 m NORTHEAST OF RANDLE REEF IN HAMILTON HARBOUR

Station 4

Visit	1		2	
Species	No./m^2	Rank	No./m^2	Rank
P. Coelenterata				
F. Hydridae				
Hydra sp.				
P. Platyhelminthes				
Cl. Turbellaria				
O. Tricladida sp. indet.				
P. Nematoda sp. indet.			15	6
P. Annelida				
Cl. Oligochaeta				
F. Naididae				
Chaetogaster diaphanus				
Ophidonais serpentina				
Stylaria lacustris				
Arcteonais lomondi				
Dero nivea				
F. Tubificidae				
Tubifex tubifex	866	4	367	5
Potamothrix moldaviensis				
Potamothrix vejdovskyi				
Limnodrilus hoffmeisteri	1,603	3	367	4
Limnodrilus cervix	124	6		
Ilyodrilus templetoni				
Spirosperma ferox				
Quistadrilus multisetosus	493	5	612	3
Immature with hair setae	1,727	2	1,714	2
Immature without hair setae	4,564	1	5,985	1
F. Lumbriculidae				
Stylodrilus heringianus				
Cl. Hirudinea				
F. Glossiphoniidae				
Helobdella stagnalis				
P. Arthropoda				
Cl. Crustacea				
O. Amphipoda				
F. Gammaridae				
Gammarus sp.				
Cl. Arachnida				
O. Acarina sp. indet.				
Cl. Insecta				
O. Diptera				
F. Chironomidae				
pupae sp. indet.				
Procladius sp.				
Chironomus sp.				
Paratanytarsus sp.				
Micropsectra sp.				
Dicrotendipes sp.				
Heterotrissocladius sp.				
P. Mollusca				
Cl. Gastropoda				
F. Valvatidae				
Valvata piscinalis				
Valvata sincera sincera				
Cl. Pelecypoda				
F. Sphaeriidae				
Sphaerium sp.				
Pisidium sp.				
Total Number of Organisms	9,377		9,060	
Total Number of Taxa	6		6	

BENTHIC DATA FOR STATION 270, LOCATED AT THE WESTERN END OF HAMILTON HARBOUR

Station 270

Visit	1		2	
Species	No./m^2	Rank	No./m^2	Rank
P. Coelenterata				
F. Hydridae				
Hydra sp.				
P. Platyhelminthes				
Cl. Turbellaria				
O. Tricladida sp. indet.				
P. Nematoda sp. indet.				
P. Annelida				
Cl. Oligochaeta				
F. Naididae				
Chaetogaster diaphanus				
Ophidonais serpentina				
Stylaria lacustris				
Arcteonais lomondi				
Dero nivea				
F. Tubificidae				
Tubifex tubifex	69	6	46	6
Potamothrix moldaviensis				
Potamothrix vejdovskyi				
Limnodrilus hoffmeisteri	941	1	846	2
Limnodrilus cervix	543	3	1,026	1
Ilyodrilus templetoni	184	5	758	3
Spirosperma ferox				
Quistadrilus multisetosus	38	7	180	5
Immature with hair setae	291	4	46	7
Immature without hair setae	593	2	536	4
F. Lumbriculidae				
Stylodrilus heringianus				
Cl. Hirudinea				
F. Glossiphoniidae				
Helobdella stagnalis				
P. Arthropoda				
Cl. Crustacea				
O. Amphipoda				
F. Gammaridae				
Gammarus sp.				
Cl. Arachnida				
O. Acarina sp. indet.			4	9
Cl. Insecta				
O. Diptera				
F. Chironomidae				
pupae sp. indet.				
Procladius sp.				
Chironomus sp.				
Paratanytarsus sp.	8	8	4	8
Micropsectra sp.				
Dicrotendipes sp.				
Heterotrissocladius sp.				
P. Mollusca				
Cl. Gastropoda				
F. Valvatidae				
Valvata piscinalis				
Valvata sincera sincera				
Cl. Pelecypoda				
F. Sphaeriidae				
Sphaerium sp.				
Pisidium sp.				
Total Number of Organisms	2,617		3,446	
Total Number of Taxa	8		9	

BENTHIC DATA FOR STATION 255, LOCATED AT THE EASTERN END OF HAMILTON HARBOUR

Station 255

Visit	1		2	
Species	No./m^2	Rank	No./m^2	Rank
P. Coelenterata				
F. Hydridae				
Hydra sp.				
P. Platyhelminthes				
Cl. Turbellaria				
O. Tricladida sp. indet.				
P. Nematoda sp. indet.				
P. Annelida				
Cl. Oligochaeta				
F. Naididae				
Chaetogaster diaphanus				
Ophidonais serpentina				
Stylaria lacustris				
Arcteonais lomondi				
Dero nivea				
F. Tubificidae				
Tubifex tubifex	145	5		
Potamothrix moldaviensis				
Potamothrix vejdovskyi				
Limnodrilus hoffmeisteri	1,891	2	3,307	2
Limnodrilus cervix				
Ilyodrilus templetoni	145	6		
Spirosperma ferox				
Quistadrilus multisetosus	436	3	689	4
Immature with hair setae	436	4	1,714	3
Immature without hair setae	3,628	1	4,332	1
F. Lumbriculidae				
Stylodrilus heringianus				
Cl. Hirudinea				
F. Glossiphoniidae				
Helobdella stagnalis				
P. Arthropoda				
Cl. Crustacea				
O. Amphipoda				
F. Gammaridae				
Gammarus sp.	8	7	15	5
Cl. Arachnida				
O. Acarina sp. indet.				
Cl. Insecta				
O. Diptera				
F. Chironomidae				
pupae sp. indet.				
Procladius sp.				
Chironomus sp.				
Paratanytarsus sp.				
Micropsectra sp.				
Dicrotendipes sp.				
Heterotrissocladius sp.				
P. Mollusca				
Cl. Gastropoda				
F. Valvatidae				
Valvata piscinalis				
Valvata sincera sincera				
Cl. Pelecypoda				
F. Sphaeriidae				
Sphaerium sp.				
Pisidium sp.				
Total Number of Organisms	6,689		10,057	
Total Number of Taxa	7		5	

Station 268

Visit	1		2	
Species	No./m^2	Rank	No./m^2	Rank
P. Coelenterata				
F. Hydridae				
Hydra sp.				
P. Platyhelminthes				
Cl. Turbellaria				
O. Tricladida sp. indet.				
P. Nematoda sp. indet.	153	11	31	11
P. Annelida				
Cl. Oligochaeta				
F. Naididae				
Chaetogaster diaphanus	31	12	31	12
Ophidonais serpentina			107	9
Stylaria lacustris	15	13		
Arcteonais lomondi				
Dero nivea	1,209	6	321	6
F. Tubificidae				
Tubifex tubifex	5,771	2	3,169	1
Potamothrix moldaviensis				
Potamothrix vejdovskyi				
Limnodrilus hoffmeisteri	7,210	1	2,541	2
Limnodrilus cervix	3,613	3	1,378	3
Ilyodrilus templetoni	475	7		
Spirosperma ferox				
Quistadrilus multisetosus	1,209	5	214	7
Immature with hair setae	245	10	429	5
Immature without hair setae	1,929	4	1,072	4
F. Lumbriculidae				
Stylodrilus heringianus				
Cl. Hirudinea				
F. Glossiphoniidae				
Helobdella stagnalis				
P. Arthropoda				
Cl. Crustacea				
O. Amphipoda				
F. Gammaridae				
Gammarus sp.				
Cl. Arachnida				
O. Acarina sp. indet.				
Cl. Insecta				
O. Diptera				
F. Chironomidae				
pupae sp. indet.	15	14		
Procladius sp.	383	8	61	10
Chironomus sp.	352	9	122	8
Paratanytarsus sp.				
Micropsectra sp.				
Dicrotendipes sp.				
Heterotrissocladius sp.				
P. Mollusca				
Cl. Gastropoda				
F. Valvatidae				
Valvata piscinalis	3	15		
Valvata sincera sincera				
Cl. Pelecypoda				
F. Sphaeriidae				
Sphaerium sp.				
Pisidium sp.				
Total Number of Organisms	22,613		9,476	
Total Number of Taxa	15		12	

BENTHIC DATA FOR THE CONTROL STATION, LOCATED 1 km NORTHEAST FROM THE MOUTH OF HAMILTON HARBOUR

Station: Control

Visit	1		2	
Species	No./m^2	Rank	No./m^2	Rank
P. Coelenterata				
F. Hydridae				
Hydra sp.	122	13	15	17
P. Platyhelminthes				
Cl. Turbellaria				
O. Tricladida sp. indet.	46	16	46	11
P. Nematoda sp. indet.	15	19		
P. Annelida				
Cl. Oligochaeta				
F. Naididae				
Chaetogaster diaphanus				
Ophidonais serpentina	138	12	31	16
Stylaria lacustris				
Arcteonais lomondi	260	9		
Dero nivea				
F. Tubificidae				
Tubifex tubifex				
Potamothrix moldaviensis	3,199	3	107	6
Potamothrix vejdovskyi	3,337	2	459	5
Limnodrilus hoffmeisteri				
Limnodrilus cervix				
Ilyodrilus templetoni				
Spirosperma ferox	398	7	31	15
Quistadrilus multisetosus	536	6	31	14
Immature with hair setae			31	13
Immature without hair setae	2,526	5	490	4
F. Lumbriculidae				
Stylodrilus heringianus	3,062	4	1,255	2
Cl. Hirudinea				
F. Glossiphoniidae				
Helobdella stagnalis	15	21		
P. Arthropoda				
Cl. Crustacea				
O. Amphipoda				
F. Gammaridae				
Gammarus sp.			15	18
Cl. Arachnida				
O. Acarina sp. indet.	46	15	46	10
Cl. Insecta				
O. Diptera				
F. Chironomidae				
pupae sp. indet.			15	19
Procladius sp.	153	10	107	7
Chironomus sp.	15	20	61	8
Paratanytarsus sp.				
Micropsectra sp.	153	11	46	12
Dicrotendipes sp.	31	18		
Heterotrissocladius sp.	31	17		
P. Mollusca				
Cl. Gastropoda				
F. Valvatidae				
Valvata piscinalis				
Valvata sincera sincera	398	8	582	3
Cl. Pelecypoda				
F. Sphaeriidae				
Sphaerium sp.	100	14	61	9
Pisidium sp.	4,087	1	2,832	1
Total Number of Organisms	18,668		6,261	
Total Number of Taxa	21		19	

Sediment bioassays on untreated sediment

Fathead Minnows:

Hamilton Harbour sediment was not lethal to fathead minnows with the exception of station 268 where complete mortality occurred within 2 days of exposure. This rapid lethality was likely due to elevated ammonia concentrations associated with the Woodward Avenue sewage treatment plant effluent. Aqueous chemical measurements generated by the Ontario Ministry of the Environment in the fall of 1988 close to the date when sediment samples were collected showed ammonium concentrations in excess of 6 $mg.l^{-1}$. This would result in at least 0.07 $mg.l^{-1}$ of unionized ammonia (at pH 7.5, 20 C) which exceeds the provincial guideline of 0.02 $mg.l^{-1}$. Subsequent bioassays were performed using sediment elutriates to differentiate between toxicity associated with solid and aqueous phases. Elutriates were prepared by continuous shaking of four parts dechlorinated, deionized tap water with one part sediment for one hour. The supernatant rapidly elicited mortality, supporting the theory that ammonia, and not contaminants more typically associated with the solid phase, was responsible for the lethal nature of the substrate.

Biomass decreased during the duration of the exposure, and was variable between sediment collected at the two visits (Table 3). This could be due to subtle differences in the nutrient composition of sediment collected at each visit. Sediment in Hamilton Harbour was higher in organic content than the

Table 3. SEDIMENT BIOASSAY RESULTS ON UNTREATED HAMILTON HARBOUR SEDIMENT, 1988.

	Hexagenia limbata		*Pimephales promelas*	
STATION	% MORTALITY (s.d.)	BIOMASS CHANGE (mg)	% MORTALITY (s.d.)	BIOMASS CHANGE (mg)
OH-1	11 (11)	21.3	0 (0)	-27.3
OH-2	30 (26)	-3.7	0 (0)	-64.0
4-1	19 (23)	17.0	7 (11)	-24.7
4-2	22 (11)	24.3	7 (11)	2.0
255-1	7 (6)	6.0	13 (11)	-9.0
255-2	22 (19)	6.3	7 (11)	-26.7
258-1	19 (17)	22.7	0 (0)	-42.7
258-2	0 (0)	19.7	0 (0)	-28.7
268-1	11 (11)	14.3	100 (0)	-
268-2	15 (13)	20.3	100 (0)	-
270-1	4 (6)	20.3	0 (0)	-72.0
270-2	4 (6)	15.7	0 (0)	-29.3
CONTROL	7 (12)	13.0	0 (0)	-52.0

TABLE 4 HAMILTON HARBOUR SEDIMENT CHEMISTRY, 1988 - 1989

SUBSTANCE	270	255	258	4	13	268	256	HONEY HARBOUR	CONTROL (OUTER HARBOUR)
Zn	2.05E+03	4.06E+03	4.61E+03	2.19E+03	1.66E+03	2.03E+03	3.27E+03	1.55E+02	1.07E+02
Cd	9.26E+00	1.52E+01	1.53E+01					4.61E+00	4.64E+00
Pb	2.86E+02	4.69E+02	5.08E+02	2.70E+02	1.50E+02	3.50E+02	4.30E+02	7.65E+01	7.51E+01
Ni	5.31E+01	7.30E+01	7.31E+01	4.70E+01	3.40E+01	4.90E+01	3.70E+01	3.43E+01	2.60E+01
Fe	6.41E+04	1.49E+05	1.11E+05					4.50E+04	3.92E+04
Mn	1.77E+03	2.78E+03	2.71E+03					1.05E+03	8.52E+02
Cr	1.40E+02	3.26E+02	2.64E+02	2.00E+02	1.25E+02	4.00E+02	4.90E+02	5.10E+01	4.45E+01
Cu	1.10E+02	2.06E+02	1.75E+02	9.50E+01	9.50E+01	1.60E+02	8.50E+01	2.40E+01	2.57E+01
Al	4.06E+04	2.61E+04	3.21E+04					3.06E+04	3.81E+04
As	1.12E+01	1.20E+01	1.46E+01	2.40E+01	1.00E+01	5.00E+00	3.30E+01	1.50E+00	
PCB	3.65E-01	2.31E-01	6.22E-01	1.54E-01	4.67E-01	8.60E-01	4.58E-01		
NAPTHALENE	6.50E-01	3.30E-01	3.58E+00	3.04E+00	4.91E+00	2.26E+00	7.47E+00		
PHENANTHRENE	1.17E+00	1.32E+00	4.12E+00	5.54E+01	1.49E+01	2.57E+00	1.55E+01		
PYRENE	2.05E+00	1.56E+00	6.33E+00	6.53E+01	2.78E+01	7.59E+00	3.45E+01		
FLOURENE	2.50E-01	2.45E+00	1.54E+00	2.87E+00	1.07E+00	5.90E-01	2.90E-01		
FLOURANTHENE	2.54E+00	1.40E+01	1.26E+01	3.41E+01	9.39E+00	5.47E+00	1.85E+00		
%TOC	4.36E+00	6.37E+00	6.27E+00	9.39E+00	9.27E+00	8.55E+00	8.10E-01	2.68E+00	3.55E+00

control sediment (Table 4) and biomass loss in controls was generally comparable to test sediment. In some cases (Station 4, Station 255) fathead minnows lost less weight in Hamilton Harbour sediment.

Thus, despite the high concentrations of trace metals, sediment was virtually non toxic to fathead minnows. Complexation of metals with either iron or sulfur compounds could have reduced the bioavailability of metals to these organisms (Jenne 1968, Di Toro et al 1990, Tessier et al 1984).

<u>Mayflies:</u>

Mayfly mortality greater than controls was observed at all stations with the exception of station 270, despite the high concentrations of Zn, Cd and Pb at this station. The outer harbour station elicited the greatest mortality when sediment from the second visit was assessed. This was attributed to the extremely sandy nature of the substrate which rendered it unsuitable for mayfly burrowing. Mayfly mortality varied among replicates and between station visits. The mean coefficient of variation between visits for mortality was 12 % $\pm$ 7%, however, the only significant difference was observed at station 258. The degree of sediment toxicity observed at these stations is in agreement with the toxicity zone map presented by Rodgers et al. (1989).

With the exception of OH-2, all mayflies increased in biomass. Growth was apparently depressed in Station 255 sediment relative to controls. This was

the only station where fathead minnow mortality exceeded 10%. Tissue residues of As, Cd, Cr, Cu, Pb and Zn tended to be the highest in mayflies exposed to Station 255 sediment as compared with those exposed to sediment from other stations. Metal toxicity could be the source of the impaired growth.

In general, tissue residues of Cd, Cr, Cu, Pb, Ni and Zn were higher in organisms exposed to Hamilton Harbour sediment than in organisms from control sediment (Table 5). PAHs were also accumulated by test organisms, however, other trace organic contaminants were not detectable, marginally above the detection limit, or not significantly different from controls (Tables 6, 7). While the lack of significant accumulation of PCBs and other compounds is encouraging, it is possible that the 21 day exposure interval was not sufficient to reveal the accumulation of higher molecular weight compounds. Kannan et al (1989) found that time to 90% uptake equilibrium of some highly clorinated coplaner PCB ranged from 31 to 85 days for the mussel <u>Perna viridis</u> Linnaeus. Similarly, steady state for PCB 1254 was not reached until day 29 by the prawn <u>Macrobranchium renbergii</u> and the clam <u>Corbicula fluminea</u> (Tatem 1986). Longer exposure to Hamilton Harbour sediment, then, may have resulted in higher PCB concentrations in test organisms.

TABLE 5. METALS IN FATHEAD MINNOWS AND MAYFLY NYMPHS FROM UNTREATED HAMILTON HARBOUR SEDIMENT, 1988/1989

FATHEAD MINNOWS

STATION	Al	As	Cd	Cr	Cu	Fe	Pb	Mn	Hg	Ni	Zn
255-1	684	1.47	0.363	11.6	26.1	2889	15.1	109	0.41	4.8	381
255-2	329	1.18	0.147	5.0	21.5	1224	5.5	48	0.48	3.1	273
258-1	579	1.95	0.379	8.2	21.8	2158	13.7	112	0.37	4.1	368
258-2	481	1.19	0.238	6.3	20.3	1794	10.5	103	0.41	2.7	268
270-1	970	1.67	0.452	8.9	25.0	2494	13.1	134	0.37	7.4	329
270-2	1433	2.06	0.928	12.6	27.1	3978	20.8	224	0.37	7.1	427
4-1	390	1.10	0.190	5.4	19.4	1429	8.5	97	0.35	2.2	278
4-2	6776	1.47	0.329	9.8	24.2	2912	13.3	164	0.41	0.7	343
13-1			0.422	6.5	6.8		5.3				183
13-2			0.511	7.2	10.3		4.4				212
CONTROL	355	0.80	0.055	1.2	14.2	660	1.0	23	0.47	1.6	202
CULTURE	7	0.52	0.021	0.4	6.4	63	0.3	2	0.18	0.3	84
OH1	994	1.06	0.206	4.9	22.3	1806	4.2	51	0.38	4.9	221
OH2	868	1.05	0.111	2.5	17.8	1516	2.3	59	0.38	1.9	235

TABLE 5. METALS IN FATHEAD MINNOWS AND MAYFLY NYMPHS FROM UNTREATED HAMILTON HARBOUR SEDIMENT, 1988/1989

MAYFLIES

STATION	Al	As	Cd	Cr	Cu	Fe	Pb	Mn	Hg	Ni	Zn
255-1	2253	13.25	1.699	35.1	41.0	11458	58.7	367	0.22	1.5	664
255-1	1888	6.13	1.463	29.5	36.4	10213	49.8	326	0.15	13.9	603
255-2	1600	4.60	1.350	28.3	35.6	8710	44.3	296	0.11	11.3	584
258-1	1770	5.60	1.280	24.7	29.9	8380	43.2	373	0.11	12.1	591
258-2	1982	7.73	1.245	26.2	32.9	10518	49.5	426	0.15	14.2	552
268-1	1604	2.19	0.927	30.0	38.9	5250	24.1	119	0.19	8.8	297
268-2	1323	1.01	1.333	20.1	34.2	4162	16.7	107	0.10	4.8	280
270-1	1969	5.26	1.031	16.7	30.7	5835	36.3	300	0.12	12.1	451
270-1	2134	5.67	1.062	18.4	31.5	6320	37.6	307	0.19	1.2	472
270-2	3104	6.04	1.521	26.6	36.1	9031	57.8	449	0.14	15.3	679
4-1	1967	3.04	1.326	22.1	31.0	8837	42.4	422	0.13	12.1	538
4-2	1764	5.73	1.100	18.9	27.5	8045	42.4	364	0.12	11.7	417
13-1			2.950	29.1	18.9		42.2				624
13-2			2.370	24.9	18.7		74.6				752
CONTROL	3689	2.56	0.611	8.0	18.0	6700	9.2	282	0.08	8.6	190
CULTURE	690	0.80	0.850	2.4	15.7	1416	2.2	98	0.07	2.3	202
OH1	2884	3.26	0.979	11.4	28.5	5474	21.7	203	0.09	10.1	208
OH2	2521	3.54	1.354	7.2	27.5	4479	11.9	236	0.07	9.0	242

all values in ug/g dry weight

'ABLE 6. PAHs IN MAYFLIES AND FATHEAD MINNOWS IN UNTREATED HAMILTON HARBOUR SEDIMENT 1988/1989. ALL VALUES IN UG/G WET WEIGH

FATHEAD MINNOWS

STATION	PHENAN-THRENE	FLOURAN-THENE	PYRENE	BENZO(a)-ANTHRA-CENE	BENZO(e) PYRENE	BENZO(b) FLOURAN-THENE	BENZO(k)-FLOURAN-THENE	BENZO(a) PYRENE	BENZO(ghi)-PERYLENE	DIBENZ(ah)-ANTHRA-CENE	IND(123-cd)-PYRENE
255-1	0.313	0.084	0.128	0.017	0.000	0.017	0.000	0.006	0.000	0.000	0.000
255-2	0.594	0.185	0.238	0.000	0.043	0.040	0.000	0.013	0.000	0.000	0.000
258-1	0.312	0.073	0.109	0.279	0.000	0.000	0.000	0.011	0.000	0.000	0.000
258-2	0.423	0.049	0.094	0.155	0.000	0.000	0.000	0.011	0.000	0.000	0.000
268-1	0.636	0.847	0.577	0.147	0.006	0.175	0.032	0.209	0.028	0.000	0.029
270-1	0.122	0.020	0.034	0.097	0.000	0.000	0.000	0.006	0.000	0.000	0.000
270-2	0.092	0.000	0.022	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4-1	1.412	0.286	0.401	0.063	0.055	0.058	0.000	0.055	0.051	0.000	0.012
4-2	0.234	0.043	0.073	0.006	0.000	0.007	0.000	0.020	0.000	0.000	0.000
13-1	0.000	0.150	0.271	0.400	0.052	0.373	0.000	0.054	0.062	0.032	0.121
OH-1	0.073	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
OH-2	0.056	0.000	0.015	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CONTROL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CULTURE	0.021	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

'ABLE 6. PAHs IN MAYFLIES AND FATHEAD MINNOWS IN UNTREATED HAMILTON HARBOUR SEDIMENT 1988/1989. ALL VALUES IN UG/G WET WEIGH'

MAYFLIES

STATION	PHENAN- THRENE	FLOURAN- THENE	PYRENE	BENZO(a)- ANTHRA- CENE	BENZO(e) PYRENE	BENZO(b) FLOURAN- THENE	BENZO(k)- FLOURAN- THENE	BENZO(a) PYRENE	BENZO(ghi)- PERYLENE	DIBENZ(ah)- ANTHRA- CENE	IND(123-cd)- PYRENE
255-1	1.150	0.826	0.840	0.273	0.014	0.227	0.092	0.342	0.057	0.000	0.040
255-2	1.827	1.381	1.368	0.473	0.030	0.390	0.122	0.585	0.094	0.006	0.071
258-1	0.041	0.022	0.009	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
258-2	1.000	0.708	0.725	0.000	0.013	0.258	0.037	0.340	0.058	0.000	0.040
268-1	0.475	0.589	0.409	0.267	0.000	0.117	0.013	0.135	0.020	0.000	0.017
270-1	0.376	0.271	0.259	0.000	0.006	0.152	0.005	0.174	0.022	0.000	0.010
270-2	0.283	0.191	0.182	0.000	0.000	0.106	0.000	0.117	0.019	0.000	0.011
4-1	3.115	1.946	1.984	0.489	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4-2	2.634	1.373	4.412	0.455	0.260	0.425	0.143	0.536	0.080	0.008	0.074
13-1	0.120	1.172	1.069	2.227	1.571	1.259	0.880	1.572	0.302	0.201	0.458
13-2	0.290	8.460	5.660	4.310	1.595	1.374	0.938	1.555	0.350	0.103	0.333
OH-1	0.084	0.048	0.033	0.012	0.000	0.013	0.000	0.004	0.000	0.000	0.000
OH-2	1.743	1.413	1.399	0.482	0.027	0.417	0.161	0.625	0.107	0.014	0.078
CONTROL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CULTURE	0.038	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 7 Trace organic compounds measured in fathead minnows and mayflies exposed to Hamilton Harbour sediment (ND = not detectable, T = trace: < 0.03 $ug.g^{-1}$, C = comparable to controls, D = detected)

COMPOUND	STATUS	DETECTION LIMIT
pp-DDE	T	0.003
pp-DDD	ND	0.010
pp-DDT	ND	0.010
op-DDT	T	0.010
a-ENDOSULFAN	ND	0.003
b-ENDOSULFAN	ND	0.005
DIELDRIN	T	0.003
ENDRIN	ND	0.003
HEXACHLOROETHANE	D	0.001
135-TRICHLOROBENZENE	T	0.002
124-TRICHLOROBENZENE	T	0.002
HEXACHLOROBUTADIENE	T	0.001
123-TRICHLOROBENZENE	T	0.002
1235-TRICHLOROBENZENE	ND	0.002
1245-TRICHLOROBENZENE	ND	0.002
26a-TRICHLOROTOLUENE	T	0.005
1234-TRICHLOROBENZENE	ND	0.001
PENTACHLOROBENZENE	ND	0.001
HEXACHLOROBENZENE	ND	0.001
HEPTACHLOR	T	0.005
HEPTACHLOREPOXIDE	ND	0.003
ALDRIN	C,T	0.005
MIREX	ND	0.005
a-BHC	C,T	0.005
b-BHC	C,T	0.010
d-BHC	ND	0.005
a-CHLORDANE	T	0.003
g-CHLORDANE	T	0.003
TOXAPHENE	ND	0.500
PCB	D,C	0.050
PHENANTHRENE	D	0.005
FLOURANTHENE	D	0.005
PYRENE	D	0.005
BENZO(a)ANTHRACENE	D	0.005
BENZO(e)PYRENE	D	0.005
BENZO(b)FLOURANTHENE	D	0.005
BEMZP(k)FLOURANTHENE	D	0.005
BENZO(a)PYRENE	D	0.005
BENZO(ghi)PERYLENE	D	0.005
DIBENZ(ah)ANTHRACENE	T	0.005
IND(123-cd)PYRENE	D	0.005

Treated sediment, toxicity evaluation experiment

<u>*Hexagenia limbata*</u>:

The effectiveness of the chemical treatments varied among sediment samples (Figure 2). For the two highly toxic sediment samples, stations 13 and 256, lethality was ameliorated by chemical treatment. The lethality of station 13 sediment was moderately decreased by dosing with lime. This station had the highest concentration of PAHs in sediment and this conformed with the highest PAH concentrations measured in tissues of mayflies. PAHs may have been important in contributing to the toxicity of this sediment, and treatments were only marginally effective at reducing mortality. The lethality of station 256 sediment was decreased by oxygen, slag and iron treatments. Oxygen and slag also decreased the lethality of sediment from station 258, while no treatments mitigated lethality of sediment from station 270. The effectiveness of the treatments at stations 256 and 258 may be due to the enhanced chelation of trace metals and consequent reduction of bioavailability. The lack of any marked effects due to treatment of station 270 sediment may pertain to its demonstrated low level of initial toxicity. That is, if a substantial portion of the metals was not in a bioavailable form, treatment would not further reduce bioavailability, and therefore, toxicity.

Growth was calculated when mortality did not exceed 50%. When mortality exceeded 50%, the biomass changes for the survivors were not brought into

consideration. The high lethality of the sediment was considered to be of primary environmental significance, making calculations of growth inhibition superfluous. In addition, measurements of growth on the surviving individuals would have been highly variable due to the small sample size. While efforts were made to use organisms of standard biomass, some variability was inevitable. Differential survival of organisms that began the experiment slightly larger than the mean biomass would bias the results.

Growth of Hexagenia was suppressed in all untreated sediment relative to the control (Honey Harbour) sediment. Treatment of sediment from station 258 by oxygen, slag, and iron improved growth relative to that observed in the untreated sediment (Figure 3). Beneficial effects of oxygen, slag and iron, as well as alum, on growth of mayflies relative to the untreated sediment were observed for sediment from station 270. The success of the chemical treatments in alleviating growth inhibition may again be attributed to the reduction of metal bioavailability in sediment, and in the case of the oxygen treatment, to the direct improvement in substrate suitability for colonization by reducing sediment oxygen demand.

Salmo giardneri:

Egg-sac stage rainbow trout were particularly sensitive to depressed oxygen concentrations. Mortality was frequently associated with oxygen depression below 5 $mg.L^{-1}$. As a consequence, variability between replicates due to reduced dissolved oxygen concentrations confounded the assessment of treatment

FIGURE 2

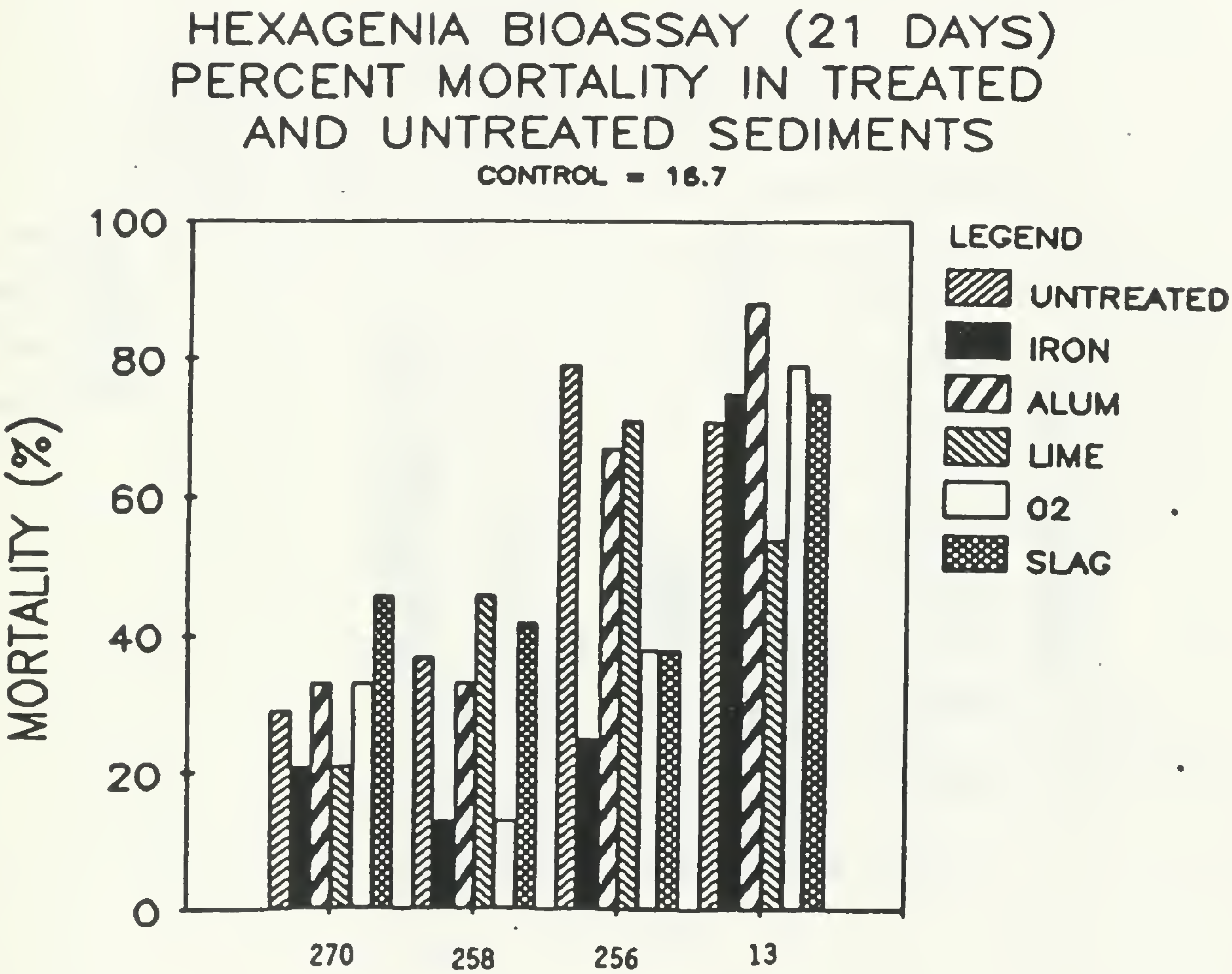
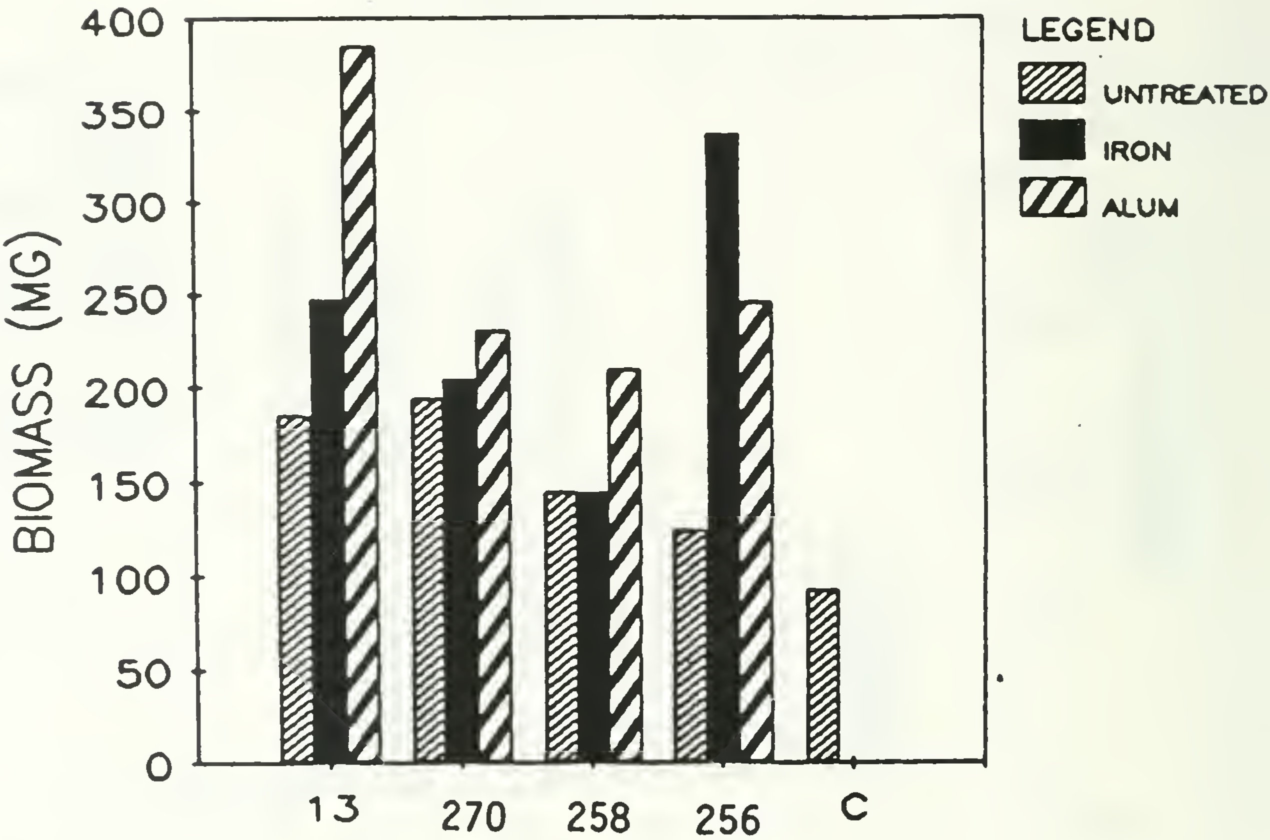

HEXAGENIA BIOASSAY (21 DAYS)
PERCENT MORTALITY IN TREATED
AND UNTREATED SEDIMENTS
CONTROL = 16.7
100
80
60
40
20
0
MORTALITY (%)
270
258
256
13
LEGEND
UNTREATED
IRON
ALUM
LIME
02
SLAG

FIGURE 5
FATHEAD MINNOW BIOASSAY
BIOMASS LOSS IN TREATED
AND UNTREATED SEDIMENTS

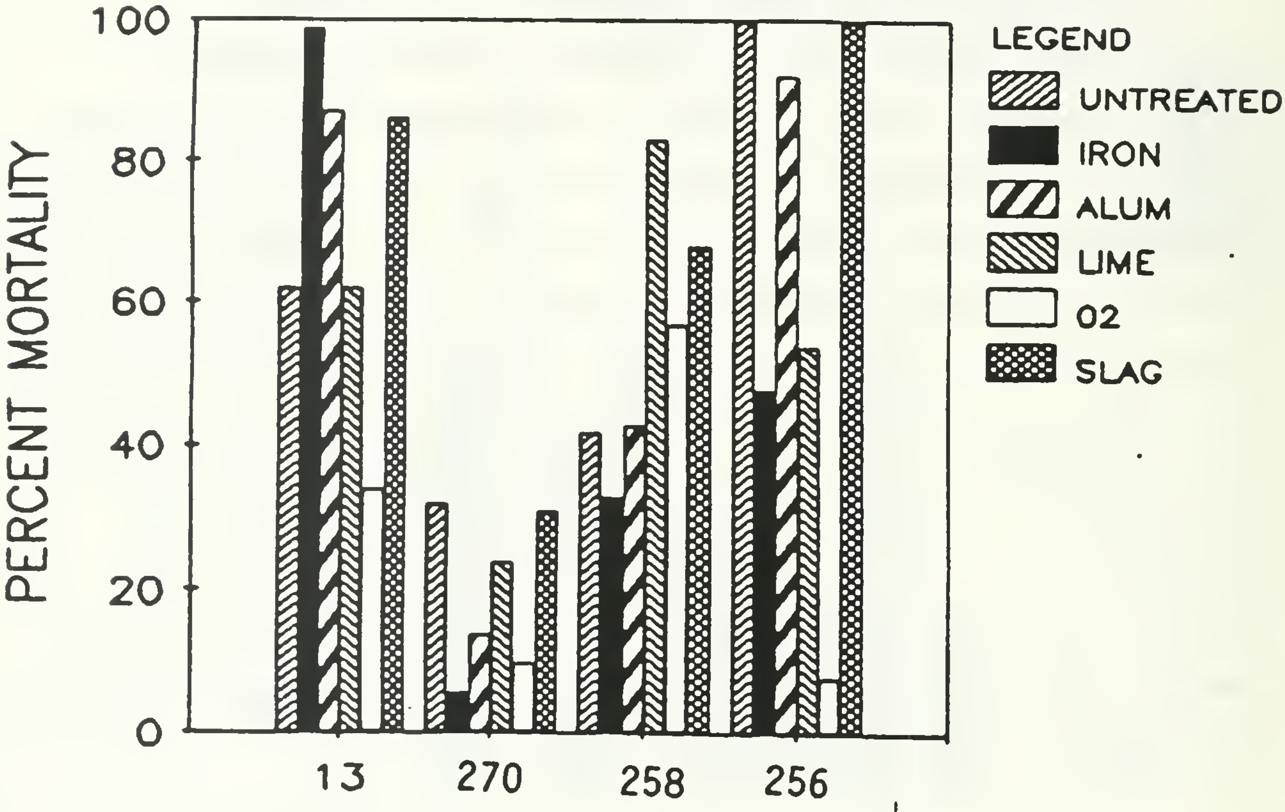


effects on mortality. In addition, no effects on growth were assessed in view of the limited number of fish surviving at the end of the bioassay.

As observed in the bioassays conducted with *Hexagenia*, mitigation of adverse consequences of exposure to the highly toxic sediment from stations 13 and 256 was provided by some of the treatments (Figure 4). However, not all treatments were equally beneficial to both species. Differential effectiveness may reflect alternate routes of exposure, with mayflies ingesting sediment as compared to passive accumulation by the egg sac stage rainbow trout. The disparate responses also point out the value of examining the response of several organisms to test sediment. For example, treatment of sediment 13 with lime was beneficial for mayfly survival but not for rainbow trout survival. Instead, oxygen was found to ameliorate toxicity of sediment 13 to *S. giardneri*. This may have been a direct consequence of alleviating the high sediment oxygen demand, rather than immobilizing metals. While oxygen, iron and slag reduced the toxicity of sediment 256 to mayflies, oxygen, iron and lime were effective in reducing mortality of rainbow trout. Oxygen, iron and alum decreased the toxicity of sediment from stations 258 and 270 relative to untreated sediment.

FIGURE 4

RAINBOW TROUT BIOASSAY
PERCENT MORTALITY IN TREATED
AND UNTREATED SEDIMENTS
CONTROL MORTALITY = 7.3%

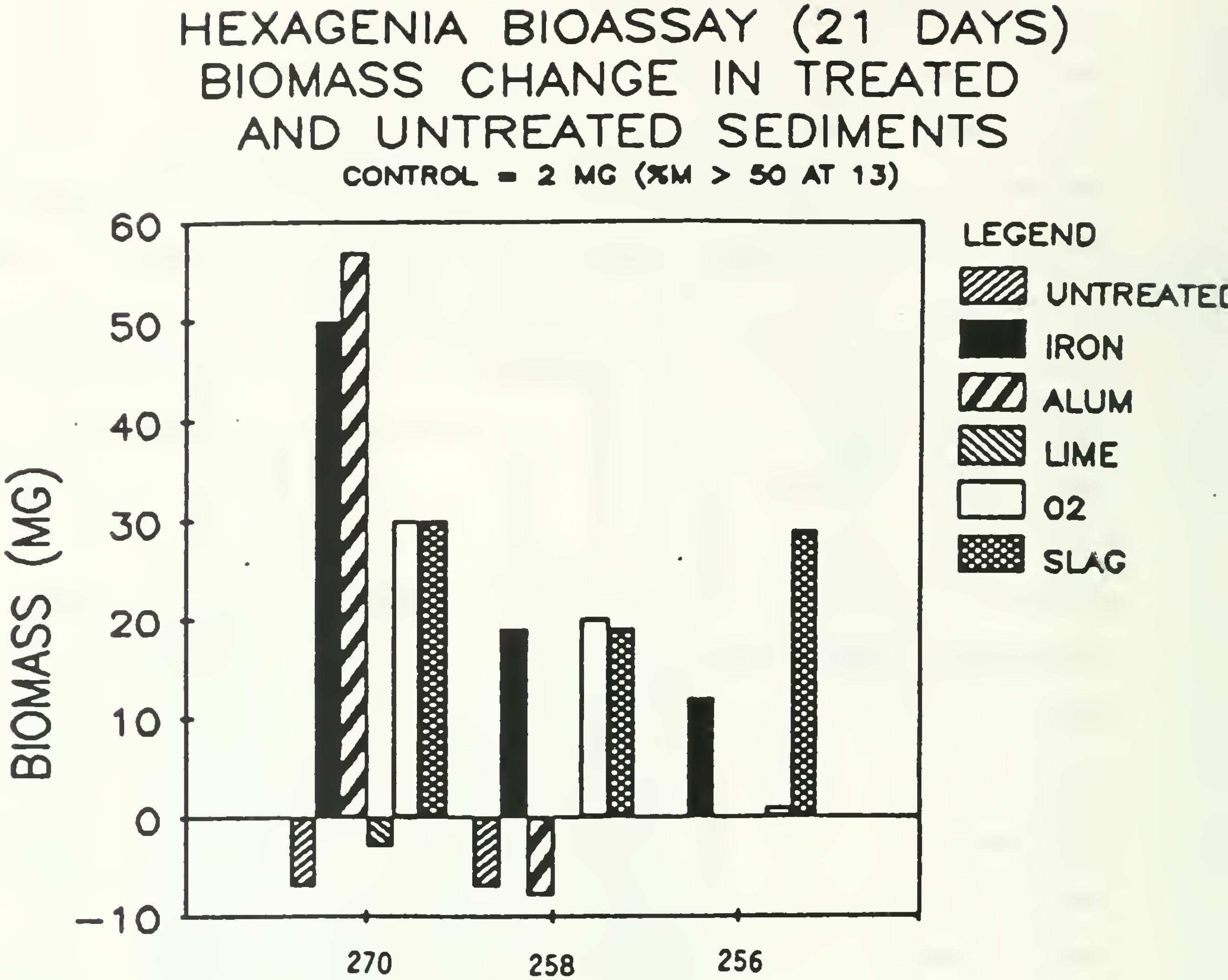


Pimephales promelas:

Fathead minnows were tested using untreated sediment and sediment treated with iron and alum. No mortality was observed in fathead minnow bioassays. In all cases, fathead minnows lost weight during the experiments. Minnows exposed to the untreated sediment, however, experienced a greater net loss in weight relative to the controls (Figure 5). The treatments were not effective at reducing sediment toxicity. Since minnows graze on sediment during the course of the experiment, the treatments may have rendered sediment less palatable, or bound nutrients as well as contaminants, resulting in no net improvement in toxicity.

The lethal and sublethal toxicity of Hamilton Harbour sediment to mayflies mirrored the restricted benthic fauna. Accumulation of metals and PAHs in test organisms in excess of controls suggests that contaminants would continue to limit benthos *in situ*, even if hypolimnetic oxygen depletion was rectified. There was some evidence from the rainbow trout assay that high sediment oxygen demand could be restricting the biota, either directly, or indirectly by altering contaminant availability (Krantzberg 1990b). Portt *et al* (1989) were unable to correlate the abundance and composition of the benthic community with contaminant concentrations because of auto-correlations between contaminant concentrations, organic composition and grain size of the sediment, depth and dissolved oxygen.

FIGURE 3


HEXAGENIA BIOASSAY (21 DAYS)
BIOMASS CHANGE IN TREATED
AND UNTREATED SEDIMENTS
CONTROL = 2 MG (%M > 50 AT 13)
60
50
40
30
20
10
0
−10
BIOMASS (MG)
270
258
256
LEGEND
UNTREATED
IRON
ALUM
LIME
02
SLAG

Conclusions

The sediment treatments were effective in reducing toxicity in some instances and the substances used are known to chelate metals, and this assists in identifying the source or cause of the toxicity. Clearly, the techniques for dosing sediment with the intention of reducing toxicity, or identifying the cause of the observed toxicity, require further development before standard toxicity reduction experiments (TRE) on whole sediment become routine.

This investigation generated several noteworthy directions for future research. It is clear that different organisms respond in different manners, perhaps as a consequence of their different life histories. Knowledge of an organism's life history can provide clues as to the mode of uptake of contaminants. Sediment in areas of the harbour that have high concentrations of metals are not necessarily toxic, and this may reflect low bioavailability of contaminants. More sensitive measurements of the bioavailable portion of metals in sediment are needed.

While the macroinvertebrate community is clearly restricted as a consequence of summer anoxia, metal contamination in some areas of the harbour is a substantive issue. This is supported by the elevated tissue residues in those bioassay organisms that experienced adverse effects of Hamilton Harbour sediment. Similarly, PAH contamination is of concern given the pronounced

tissue residues and toxicological responses of test organisms exposed to contaminated sediment from some locations.

References

Campbell, P.G.C., A.G. Lewis, P.M. Chapman, W.K. Fletcher, B.E. Imber, S.N. Luoma, P.M. Stokes, M. Winfry. 1987. Bioavailability of sediment bound trace elements. Canadian National Research Council Publication.

Campbell, P.G.C., A. Tessier, M. Bisson and R. Bougie. 1985. Accumulation of copper and zinc in the Yellow Water Lily, Nuphar varegatum: Relationships to metal partitioning in the adjacent lake sediments. Can. J. Fish. Aquat. Sci. 42 23-32.

Chapman, P.M. 1989. Current approaches to developing sediment quality criteria. Environ. Toxicol. Chem 8: 589-599.

Davies-Colley, R.J. P.O. Nelson, K.J. Williamson. 1985. Sulfide control of cadmium and copper concentrations in anaerobic estuarine sediments. Mar. Chem. 16: 173-186

Di Toro, D.M. J.D. Mahony, D.J. Hansen, K.J. Scott, M.B. Hicks, S.M. Mayr, M.S. Redmond. 1990. Toxicity of cadmium in sediments: The role of acid volatile sulfide. Environ. Toxicol. Chem (submitted)

International Joint Commission. 1988. Procedures for the assessment of contaminated sediment problems in the Great Lakes. Report to the Great

Lakes Water Quality Board.

Jenne, E.A. 1968. Controls on Mn, Fe, Co, Ni, Cu and Zn concentrations in soils and water: the significant role of hydrous Mn and Fe oxides. p. 337-387 in: Gould, R.F. (ed.) Trace Inorganics in Water. Amer. Chem Soc., Washington, D.C.

Kannan, N., S. Tanabe, R. Tatsukawa and D.J.H. Phillips. 1989. Persistency of highly toxic coplanar PCBs in aquatic ecosystems: uptake and release kinetics of coplanar PCBs in Green-lipped mussels (Perna viridis Linnaeus). Environ. Pollut. 56: 65-76.

Karr, J.R. 1987. Biological monitoring and environmental assessment: a conceptual framework. Environ. Management 11: 249-256.

Krantzberg G. and P.M. Stokes. 1988. The importance of surface adsorption and pH in metal accumulation by chironomids. Environ. Toxicol. Chem 7: 653-670.

Krantzberg, G. 1990a. Sediment Bioassay Research and Development. Report to the Ontario Ministry of the Environment Research Advisory Committee, PDF03. ISBN # 0-7729-7147-1.

Krantzberg, G. 1990b. The role of oxygen in the toxicity of Hamilton Harbour sediment. (in prep)

Landner, L. 1988. Hazardous chemicals in the environment - some new approaches to advanced assessment. Ambio 17: 360-366

Luoma, S.N. 1983. Bioavailability of trace metals to aquatic organisms -- A review. Sci. Total Environ. 28: 1-22

Persaud, D., R. Jaagumagi and A. Hayton. 1990. Provincial sediment quality guidelines, A discussion paper on their development and application. Draft Report of the Ontario Ministry of the Environment, February 1990.

Portt, C.B., V.W. Cairns, C.K. Minns, and R. Dermott. 1989. Benthic macroinvertebrates and sediment characteristics in Hamilton Harbour: Current conditions and changes between 1964 and 1984. Cited in Rogers et al. 1989.

Rodgers, K., J. Vogt, V. Cairns, D. Boyd, L. Simser, C. Selby, H. Lang, T. Murphy, and S. Painter. 1989. Remedial Action Plan for Hamilton Harbour. Environmental Conditions and Problem Definition. 162 pp.

Tatem, H.E. 1986. Bioaccumulation of polychlorinated biphenyls and metals from contaminated sediment by freshwater prawns, Macrobrachium

rosenbergii and clams, *Coribicula fluminea*. Arch Environ. Contam. Toxicol. 15: 171-183.

van Veen, H.J. and P.B.M. Stortelder. 1988. Research on contaminated sediments in the Netherlands. p. 1263-1275. in: K. Wolf, W.J. van den Brink, F.J. Colon (eds) Contaminated Soil '88.